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Mechanical Beam Isolator

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ABSTRACT

Back-reflections from a target, lenses, etc. can gain energy passing backwards through a laser just like the main beam gains energy passing forwards. Unless something blocks these back-reflections early in their path, they can seriously damage the laser. A Mechanical Beam Isolator is a device that blocks back-reflections early, relatively inexpensively, and without introducing aberrations to the laser beam.

1. INTRODUCTION

Future laser driver designs may be able to exploit significant advances in the technology of high-speed flywheel energy storage systems by adapting elements of the technology for use in laser beam isolation. The Energy Directorate of the Laboratory has developed novel bearing and permanent-magnet motor designs for electromechanical batteries (EMBs - flywheel energy-storage modules). These EMBs employ fiber-composite rotors capable of operation at very high rotation speeds, with peripheral velocities of order 2000 m/s. At these velocities, the use of a mechanical beam isolator near the focal plane of a spatial filter of a laser may become feasible (see Figure 1).

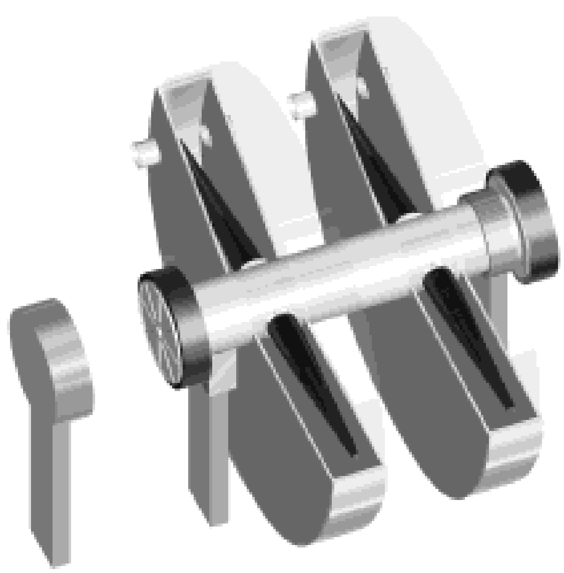


Figure 1. Artists rendition of a Mechanical Beam Isolator

Back-reflections from a target, lenses, etc. can gain energy passing in the reverse direction through a laser system, in the same way that the main beam gains energy in the forward direction. Unless these reflections are blocked early in their path they can seriously damage the laser system. A Mechanical Beam Isolator is a device that blocks back-reflections early on, is relatively inexpensive compared to alternative techniques, and does not introduce optical aberrations in the laser beam.

All large laser systems have some type of beam isolation. For example, the Nova laser at Lawrence Livermore National Laboratory and Phebus at Centre d'Etudes de Lemeil-Vatleton (CEL-V), France both use Faraday rotators and polarizers to prevent back-reflections from propagating in the reverse direction through these one-pass lasers. In LLNL's newer, four-pass lasers, Beamlet and in the proposed National Ignition Facility (NIF), a large Plasma Electrode Pockels Cell (PEPC) and polarizer provide the necessary beam isolation. In these four-pass lasers, the Pockels cell and polarizer have the additional function of switching the beam out of a closed cavity.

By contrast, the French Laser MegaJoule (LMJ) laser is an open cavity design. It uses a Reverser, small optics in the transport spatial filter, to turn the beam around (after two passes) for another two passes through the amplifiers (see Figure 2). The Reverser was successfully tested on Beamlet; however, the need for better isolation against back-reflections was identified in these tests. The newly conceived Mechanical Beam Isolator described in this report appears to provide that needed protection.

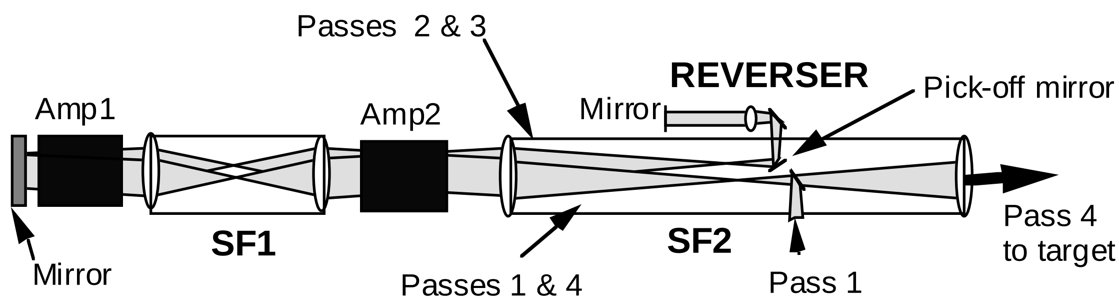


Figure 2. The Reverser makes a two-pass laser into a four-pass laser

The idea of a mechanical "shutter" in high-power laser systems is not new: it was seriously considered for the Nova laserbut the technology at the time was not sufficient. For example the composite material then selected had a strength of 0.5 GPa. Today, commercial graphite fibers for use in fiber composites have strengths of order 7.0 GPa, and fibers of yet higher strength have been manufactured in pilot-plant production. As a result of these developments and because of new design concepts for the geometry of the isolator the concept of a mechanical beam isolator can become a reality.

The Mechanical Beam Isolator (MBI) described herein consists of two rotating rods composed of graphite fiber-composite. These bars penetrate through a central shaft so that they rotate about an axis passing through their midplane (see Figure 3). Each rod is cylindrical in cross-section and is of order 50 cm in length. The diameter of a rod at its midsection is about 2.5 cm, tapering down towards its ends in gaussian fashion. The purpose of this particular geometry, as can be shown by theory, is to maximize the attainable tip velocity. The orientation of the rod-shaft assembly is such that the rods rotate about an axis that is parallel to the laser beam direction. By locating the rods on a common hub, with the stationary pinhole positioned between one effectively halves the closing time of the isolator. Since the beam inverts during focus at the pinhole, each rod blocks opposite parts of the beam, even the two rods lie in a common plane passing through the axis.

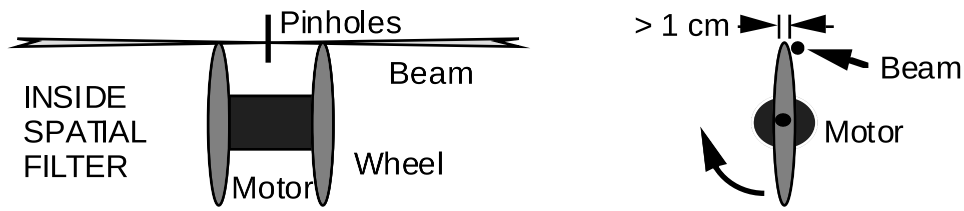


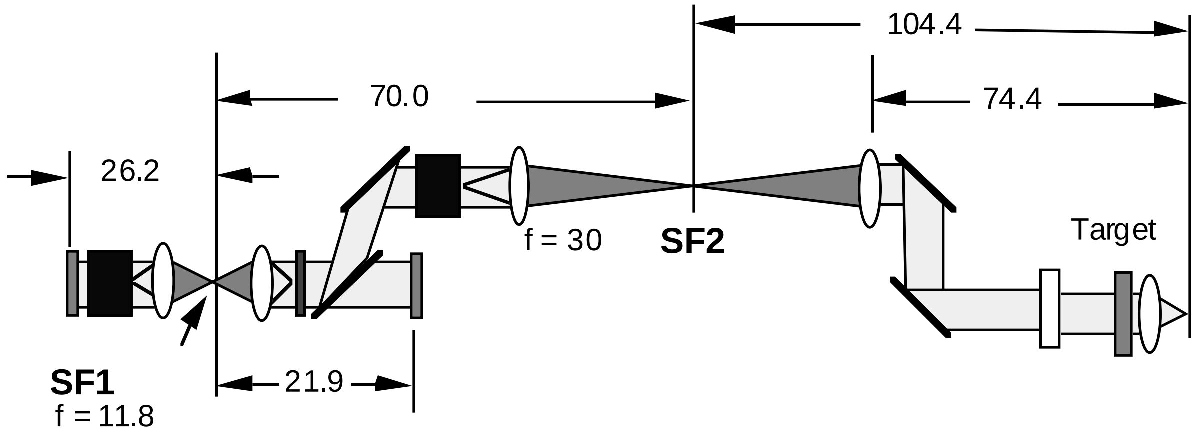
Figure 3. Schematic of a mechanical beam isolator

Preliminary measurementshave been made of the ablation of the material at the tip of the rods that is to be expected in the use of a MBI in a laser such as NIF. Even though the amounts of material that is ablated is small some degree of unbalance might be expected to occur. Two ways to ameliorate this problem have been considered. First, the bearing system that is proposed is a so-called "passive" magnetic bearing system that is inherently insensitive to modest degrees of unbalance. Second, by design of the electronic drive system it could be arranged that, on average, opposite tips of a given rod would receive the same number of ablating pulses, thus tending to preserve the initial balance.

In operation the rods are synchronized to pass the shot pulse but block all light for a period of about 1.15 ms after the pulse. At the proposed tip velocities (about 2 mm/ms) this would require a diameter at the tip of about 2.5 mm. The tip would have to absorb 100 plus Joules of back-reflected laser energy in a typical case, depending on the location of the MBI in the laser. As will be discussed later, calculations indicate that a 2 mm pinhole could be blocked in about 0.2 ms with the rods operated at 70 percent of their ultimate strength. This short blocking time would protect the laser against back reflections from targets and from other pinholes.

2. LOCATIONS FOR THE MBI

Where the MBI is located in the laser amplifier chain and what its tip velocity is determine which back-reflections it can block. Both the LMJ and the NIF lasers have two spatial filters. For discussion purposes, we will call the spatial filter nearest the target, Spatial Filter Two (SF2) and the other filter, Spatial Filter One (SF1). At the point of beam focus, inside the spatial filter, is a pinhole mechanism with pinholes numbered for each pass the beam makes, Number One for the first pass up to Number Four for the last pass. Since SF2 relays the beam from the laser to the target area it is relatively long, 65 meters in NIF and 55 meters in LMJ. Spatial filter SF2 is much shorter, being 22 and 15 meters, respectively. The pinhole size in the NIF and LMJ spatial filters is about 2.0 mm in SF1 and 6.0 mm in SF2. Options for locating the MBI in a NIF beamline and the associated reflection times are given in Table I. One-dimensional smoothing by spectral dispersion (1D-SSD) is assumed, so that the pinholes are elliptical in shape (minimum dimension given in the Table) to accommodate beam steering in the moving dimension. The pinhole sizes would be larger if 2D-SSD were to be implemented.



Option	Location	Pinhole	Reflections blocked	Pinhole size (mm)	Earliest return (µs)	Tip Vel. (m/s)	RPM
1	SF2	Ph4	Target	6	0.69	4347	166,075
2	SF1	Ph4	Target	2	1.15	870	33,215
3	SF1	Ph4	Target & PH4	2	0.46	2173	83,037
4	SF1	Ph1	Target	2	2.13	469	17,933
5	SF2	Ph1	Target	6	2.59	1158	44,244
6	SF2	Ph1	Target & PH2	6	0.81	3703	141,795

* Light travels 100 m in 0.33µs

Table 1, Options for locating the mechanical beam isolator in a NIF beamline

Locating the MBI to block Pinhole Four in SF2 (Option 1) has the advantage of blocking target reflections before they enter the laser. However, the pinhole is large, 6.0 mm, requiring tip velocities that push the limits of materials and technology.

Furthermore, this location would provide no protection against back reflections from the last pinhole (Pinhole Four in SF2), the one most likely to generate a back reflection. During large energy shots, considerable laser energy is clipped out the beam by the pinhole mechanism, with the last pinhole clipping the most energy. If the beam is not well aligned this energy can be high enough to form a plasma which reflects light back into the laser. No conceivable MBI could be fast enough to block a light pulse originating only a few centimeters away from its location.

Blocking target reflections at Pinhole Four in SF1 (Option 2) is comparatively easy, requiring a tip velocity of only 870 m/s. In part the slower tip velocity required is due to more time to close the hole, but the primary benefit here is that there is a smaller hole to close. If the tip velocity is increased to about 2200 m/s (Option 3), blocking reflections from the last pinhole seems feasible. Compared to Option 1, energy reflected from the target or last pinhole has been amplified by about a factor of four upon return, but the capability of blocking both target and final pinhole reflections compels us to recommend this location. Blocking the beam on pass 3 would allow a longer closing time but is impractical because the reflections would have gained too much energy, having passed through the main amplifier twice.

An MBI located in SF1 will be synchronized to pass the shot pulse but fully close the hole in 0.46 ms, stopping possible reflections from Pinhole Four and any other reflections as late as 1.15 ms delay from the target. At a tip velocity of 2200 m/s, this requires a tip 2.5 mm in diameter to keep the hole closed against all back reflections. The tip may also need to absorb several hundred Joules of back-reflected laser energy. As noted previously, the ablation that this will cause will tend to result, over time, in an unbalancing of the rotors that must be accommodated by the bearing system. While erosion of the tip is to be expected, the mean time between replacements must be tenable. Preliminary measurementsmade at LLNL are encouraging in this regard but more tests are needed.

The requirement for relative insensitivity to unbalance is one that seems to preclude the use of conventional mechanical bearings to support the shaft. As also noted earlier, the passive magnetic bearings that are proposed to be used should not be sensitive to moderate degrees of unbalance.

In case of a catastrophic failure of a rotor rod the resulting fragments must be contained. Experience gained in the EMB program at LLNL provides guidelines for the development of containment envelopes for the rotors. The constraints imposed by the laser imply the use of pancake-shaped containment "cans", one for each rotor, that are about 60 cm in diameter and a few centimeters thick, with reentrant tubes near their periphery to pass the beams.

Even with a system using a full-aperture PEPC, the MBI may be employed to reduce the size and cost of isolating the front-end of the laser. The PEPC cannot block all the back-reflected light; the percentage of leakage is small, but it passes twice through the main amplifier with substantial gain. Up to 100 Joules of highly modulated energy could be expected to enter the preamplifier. In contrast, the maximum output energy from the preamplifier is about 12 Joules, meaning that the optics must be over-sized and more expensive to avoid damage from back-reflections. An MBI used here could prevent any back-reflected energy from entering the preamplifier. In this case, the MBI would block Pinhole One, but would still be located in either SF1 (Option 4 and 5) or SF2 (Option 6). This early in the laser, the required tip velocities are relatively low, unless there is also a desire to block reflections from Pinhole Two in SF1 (Option 6).

Regardless of where the MBI is placed in the laser system, it has the marked advantage of non-contact with the pulsed beam, i.e., it introduces no optical aberrations or losses, nor does it exacerbate non-linear beam modulation. Eliminating beam aberrations induced by an optical isolator system improves beam quality, correspondingly allowing higher energy to be achieved from the laser with incurring optical damage. Eliminating the optical losses that are associated with an optical isolator system means that less gain is required, possibly resulting in fewer amplifier slabs to produce the same laser output. Removing the many centimeters of optical material associated with the windows and the KDP crystals of full-aperture PEPCs would significantly lower the non-linear growth of beam modulation on the last pass of the beam, thereby allowing the amplifier slabs to be arranged more efficiently.

3. CONTRIBUTIONS FROM FLYWHEEL TECHNOLOGY: MBI DESIGN

In the conceptualization and design of the MBI there are several areas where the experience at LLNL in developing flywheel energy storage modules (i.e., EMBs) has contributed to the feasibility of the MBI. One example is making the flywheel rotors out of the same super-strength composite materials used in the energy storage modules. High tensile strength is of course a sine qua non for the achievement of high tip speeds, since the speed is limited by tensile failure caused by centrifugal forces. The composite materials, graphite fibers mixed with epoxy resins, are the highest strength material commercially available. Particularly strong are "uni-directional fiber composites where the fibers lie parallel to each other in the composite, maximizing the tensile strength in that direction. An elongated, gaussian shape for the rotors was suggested to take advantage of this characteristic.

With strengths of high-quality fibers approaching 7.0 GPa, and utilizing a typical mix of 65 percent fiber, 35 percent epoxy, the tensile strength of the composite is 4.5 Gpa -- three times that of alloy steel. Of even greater importance for the achievement of high tip speeds is the fact that the density of the fiber composite is much lower than that of steel - typically 1550 kg/m^3 vs. 7800 kg/m^3 . As discussed later, the achievable tip speed from a rotor is proportional to $\sqrt{S/r}$, where S is the tensile stress (caused by the centrifugal force field) and r is the density. Comparing alloy steel and the fiber composite, then, one finds a ratio of limiting tip speeds in excess of 4:1 in favor of the composite. Also, as discussed below, the particular geometry chosen for the rotor shape, a gaussian-tapered rod, further increases the achievable peripheral speeds over those achievable with a cylindrical-shaped rotor.

Indeed, the form of a flywheel rotor has a strong influence on the maximum speed that it can be run before tensile failure. With metal flywheels the Stodola rotor[6], a disc whose thickness tapers down exponentially with radius, is an example of optimizing the attainable peripheral speed. As will be derived below, the optimum taper for the cross-section of the rods of our MBI is not exponential but gaussian.

3.1 Geometry of the rotor rods

We will approach the problem analytically by posing the following question: Is there a taper function for a thin rod rotating about an axis through its midplane such that the tensile stress in the rod is independent of radius at all radii (including infinite radius)?

We begin by defining the radial tensile stress at any radius in terms of the centrifugal force, F(r), arising from the remainder of the rod beyond that radius. This equation is:

$$F(r) = rw^2 \int_r^{\bullet} A(r')r'dr' \qquad \text{Newtons} \tag{1}$$

where A(r) m is the cross-sectional area of the rod. Now require that the stress, S(r) = F(r)/A(r) be a positive constant, independent of the radius, r. Normalizing S(r), this condition is equivalent to the requirement:

$$\frac{\int_r^{\bullet} A(r')r'dr'}{A(r)} = k^2 = \text{constant} \tag{2}$$

We now multiply both sides of this equation by A(r) and take the derivative with respect to r of this expression, yielding a differential equation for A(r):

$$-rA(r) = k^2 \frac{dA(r)}{dr} \tag{3}$$

The solution to this differential equation, with A= A(r=0) is:

$$A(r) = A_0 \exp\left[-\frac{r^2}{2k^2}\right] \quad m^2 \tag{4}$$

Thus, in principle, if the rod area is tapered in a gaussian manner the tip velocity can be made arbitrarily high (requiring, of course, an infinitesimally small diameter at its end). Practical limitations will define the amount of taper that can be tolerated, but, as we shall see, the gains (over a non-tapered rod) are substantial.

If we now consider a truncated gaussian rod, that is, one with a finite ratio of its diameter at the tip to that at its midplane, the expression for the tensile stress as a function of radius becomes:

$$S(r) = \frac{1}{2}\, r w^2 a^2 \left\{ 1 - \exp\left[- \frac{r_{max}^2 - r^2}{a^2} \right] \right\} \quad Nm^{-2} \qquad (5)$$

It is instructive to compare the maximum tensile stress and the profile of the tensile stress in a gaussian tapered rod as compared to a rod of uniform diameter (obtained by taking the limit in equation (5) as aÆ•). This comparison is shown in Figure 4, which plots the relative tensile stress as a function of position along the rod for (1): a 0.5 m. long gaussian tapered rod with a diameter ratio, D, (diameter at the tip compared to diameter at its midplane) of 0.1, and (2) a constant-diameter rod of the same length and rotating with the same tip speed. The relative constancy and the much lower value of the peak stress in the tapered rod is apparent.

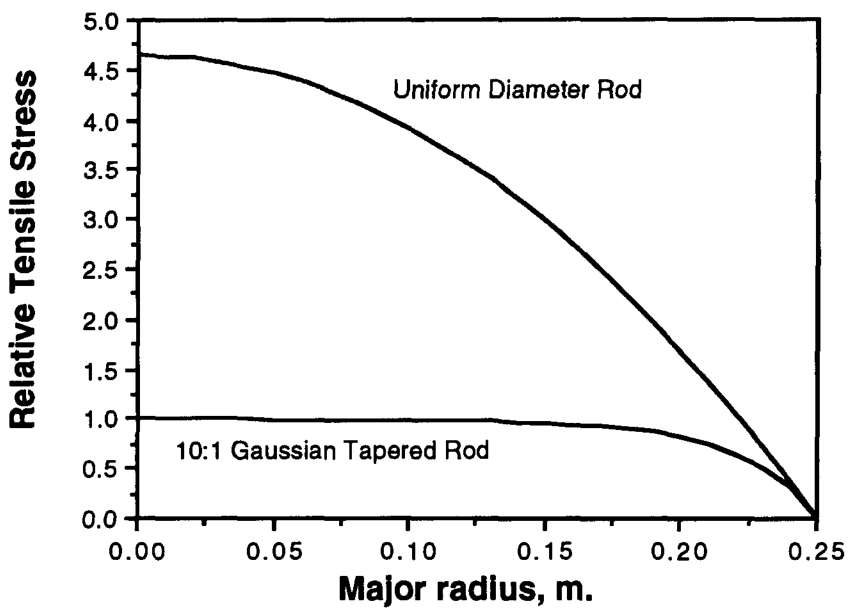


Figure 4. Relative tensile stress along the rod

Since the tip speed of the rod is given by the value of the quantity (wr_{max}) we may use equation (5) to derive an expression for the tip speed, v_t, in terms of the tensile stress at r = 0, the density of the composite, r, and D, the ratio of the diameter of the rod at its tip to that at its center:

$$v_t = 2\left[\frac{\ln(1/D)}{1-D^2}\right]^{1/2}\sqrt{\frac{S(r=0)}{r}} \quad \text{m/sec.} \qquad (6)$$

We may now use the fiber-composite parameters previously stated for graphite-epoxy fiber-composite, namely, S= 4.5 GPa, and r = 1550 kg/m^3 , to evaluate the attainable tip speed as a function of the above parameters. Figure 5 is a plot of the tip speeds as a function of D, for three different values of the tensile safety factor, 1.0 (i.e., operation at the tensile strength limit), 1.5, and 2.0. The latter two values probably represent the general range that one would wish to operate in, although with special care a safety factor lower than 1.5 might be acceptable. Note that the abscissa of the plots is given in units of mm/ms (1 mm/ms = 1000 m/s). These plots show that it seems feasible to design an MBI with tip speeds of order 4 to 5 mm/ms, a substantially higher value than that obtainable with any conventional geometry, such as a disc or a uniform-diameter rod. (Note that the case of the uniform rod corresponds to the value D = 1.0, i.e. the right-hand edge of the plots.)

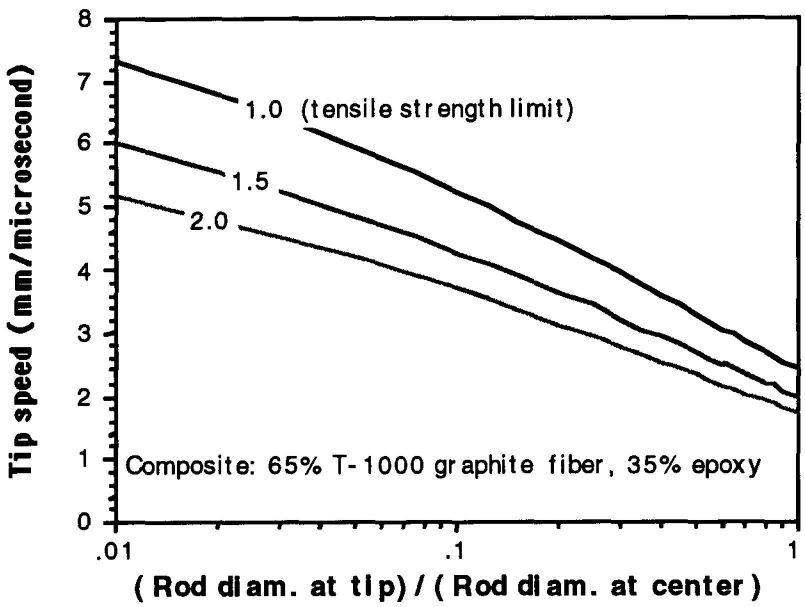


Figure 5. Tip speeds as a function of rod diameter

The discussion to this point has been aimed at the issue of tensile stresses in the rods. However, one must also consider the presence of shear stresses that result from the redistribution of stresses in the rod as a function of its geometry. Intuitively, one can expect that in rods with a small aspect ratio (ratio of rod diameter at the midplane to the rod length) the shear stresses would be very small. This intuitive result is borne out by some calculations that have been made at the Laboratory[7] , using the NIKE 3-D finite element code. In a representative case maximum shear stresses that were less than 1 percent of the tensile strength of the composite were found, well within the acceptable levels for shear stress in this type of fiber composite. The same calculations showed that by judicious choice of the values of D and of the central rod diameter one should be able to arrive at designs that optimize the safety factor for both the tensile and the shear stresses.

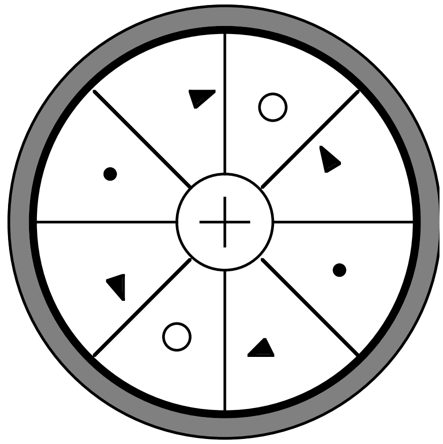
We conclude from this that the tip speeds stated in Section II can be achieved.

3.2 Halbach array motors

The second area where the LLNL experience with EMBs contributes to the development of an MBI is the area of high-speed, highly efficient, drive motors and their associated electronics. In the Livermore work**,** a particular form of a generator/motor has been chosen, based the use of a special array of permanent magnets in its rotor. The motor is excited by air-cored stator windings, i.e., the motor is "ironless" in that no laminated iron structures are used. In EMBs, these motors have reached speeds in excess of 60,000 RPM **--** limited by the strength of the rods and not by motor performance.

The permanent-magnet array proposed for the MBI is known as a Halbach array[8], devised originally for use in particle accelerators. Halbach arrays can be configured in either a cylindrical or a planar form. The basic concept involved here is to orient the dipole moments of a periodic array of permanent magnets in such a way that the fields produced by these dipoles add constructively on one side of the array, for example within a cylindrical region, while canceling on the opposite side of the array. In this way the magnets are utilized optimally without the requirement for use of "back iron" or magnetizable pole faces. In the Livermore EMB program both cylindrical and planar Halbach arrays have been employed, either in the generator/motor assemblies or in passive magnetic bearings.

For the MBI it is proposed to use two planar Halbach arrays, one mounted at each end of the shaft that carries the rods. An end view of the assembly of permanent magnets, showing the orientation of their directions of magnetization is depicted schematically in Figure 6. The array shown in the figure is one that creates a periodic magnetic field with mainly azimuthally (f) and axially (z) -directed field components having the periodicity cos(2f) or sin(2f). The motor assembly would then be completed by mounting an air-core stator with planar windings facing the Halbach array.



Planar Halbach array

Figure 6. Permanent magnets in a Halbach array motor

As has been demonstrated in the EMBs developed at Livermore, Halbach array motors are extremely efficient, with electrical-to-mechanical conversion efficiencies in excess of 98 percent being achievable. High efficiency then greatly simplifies the problem of cooling the stator windings when these windings are within an evacuated region, as they will be in the MBI. The high efficiency is owing in large part to the fact that there are no laminated iron structures in the assembly with their accompanying hysteresis losses. For the same reason, there are no appreciable losses associated with the harmonic content of the driving wave forms. This circumstance leads to a substantial simplification of the electronic drive circuitry, which can now employ simple circuits generating square waves to power the windings.

3.3 The issue of bearings

The issue of bearings and rotor-dynamic issues associated with them is a very important one for the MBI. In considering the various options for bearings, we have examined three possibilities: (1) mechanical (ball bearings), (2) active magnetic bearings, and (3) ambient-temperature passive magnetic bearings. For reasons of cost and operational complexity, we rejected a fourth possibility: passive magnetic bearings employing high-temperature superconducting elements. Of the three, we have selected the ambient-temperature passive magnetic bearing for our designs.

The factors that influenced our selection were: cost, simplicity, sensitivity to unbalance, reliability, service life, and contamination (as associated with lubricants in mechanical bearings). We ruled out mechanical bearings because of issues with contamination, sensitivity to unbalance, and limited service lifetime at high speeds. While active magnetic bearings should certainly be suitable from the standpoint of contamination and insensitivity to unbalance, their cost and their perceived failure probability ruled them out in our minds.

3.4 Ambient-temperature magnetic bearings

As a component of the EMB developments at Livermore**,** concepts have been developed and tested that permit the design of passive magnetic bearing systems. The Livermore ambient-temperature magnetic bearings utilize a combination of static forces from permanent-magnet elements combined with electrodynamic effects arising from periodic permanent-magnet arrays (such as the Halbach array) to overcome the classic instability of such bearing systems (as predicted by Earnshaw's theorem) For a detailed description of the concepts involved see the patent reference cited.

4. CONCLUSIONS

We have described a concept for a mechanical beam isolator which could protect multi-pass laser systems from back-reflection damage. We showed that the MBI rods and motor could achieve the super rotation speeds required. We also explain how this technology leverages off years of experience at Livermore in the development of modular flywheel energy storage systems. This technology base should be an adequate foundation to produce a mechanical beam isolator in the near future.

5. ACKNOWLEDGMENT

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